

A magnetic cycle of τ Bootis? The coronal and chromospheric view

K. Poppenhaeager^{1,*}, H.M. Günther², and J.H.M.M. Schmitt¹

¹ Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany

² Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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τ Bootis is a late F-type main sequence star orbited by a Hot Jupiter. During the last years spectropolarimetric observations led to the hypothesis that this star may host a global magnetic field that switches its polarity once per year, indicating a very short activity cycle of only one year duration. In our ongoing observational campaign, we have collected several X-ray observations with XMM-Newton and optical spectra with TRES/FLWO in Arizona to characterize τ Boo's corona and chromosphere over the course of the supposed one-year cycle. Contrary to the spectropolarimetric reconstructions, our observations do not show indications for a short activity cycle.

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1 Introduction

Magnetic activity is an ubiquitous phenomenon in late-type stars and manifests itself in both short-term processes such as flares and coronal mass ejections as well as in long-term observables such as the solar eleven-year activity cycle. For a multitude of cool stars such cycles of several years duration have been found by monitoring their chromospheric activity indicators (Baliunas et al. 1995); however, a thorough understanding of stellar activity cycles and their dependence on fundamental stellar parameters is still missing.

Especially for planet-hosting stars the stellar activity is highly interesting as high-energy radiation, stellar wind and coronal mass ejections are expected to have a strong influence on the outer planetary atmosphere. Planets have been detected around stars of very different activity levels. The first (radial-velocity) detected planet 51 Peg b probably orbits a Maunder minimum star (Poppenhäger et al. 2009), while especially space-based transit observations have also discovered planets around young and active stars like Corot-2 (Alonso et al. 2008). In addition, several stars with indications for an activity cycle similar to the solar sunspot cycle have been found to host planets, such as ι Hor (Metcalf et al. 2010) and τ Boo, the latter of which is closely investigated for its coronal and chromospheric activity in this paper.

τ Boo is a planet-hosting main sequence star of spectral type F7 located at 15.6 pc distance from the Sun. Its age has been estimated to be roughly 3 Gyr from isochrones, lithium abundances and chromospheric Ca II activity (Saffe et al. 2005). For this age, the star rotates rather fast with a mean rotation period of $P_* = 3.23$ d; it also displays quite strong differential rotation with $P_{\text{eq}} = 3$ d and $P_{\text{pole}} = 3.9$ d at the

Table 1 XMM-Newton and optical observations of τ Boo with exposure time t given and expected activity state as extrapolated from magnetic field reconstructions.

Obs. ID	Obs. Date	t (ks)	State
0144570101	2003-06-24	70.5	min.
0651140201	2010-06-19	12.7	min.
(optical)	2010-06-19	2.2	min.
0651140301	2010-07-23	7.7	min.
(optical)	2010-07-24	1.7	min.
0651140401	2010-12-19	9.7	max.
0651140501	2011-01-22	13.3	max.
(optical)	2011-04-(07-18)	6.2	int.
0671150501	2011-06-19	11.6	min.
(optical)	2011-07-(15-17)	6.1	min.

equator and the poles, respectively (Donati et al. 2008). It has been speculated that this fast rotation stems from a tidal spin-up induced by the giant planet that orbits the star with a period of 3.3 d (Barnes 2001).

Even if magnetic activity is not understood well enough to predict durations and strengths of activity cycles from fundamental stellar parameters, a short activity cycle might be expected for τ Boo as stellar rotation and magnetic activity are related in late-type stars. In the Mount Wilson program (Baliunas et al. 1995), the star did not exhibit strong periodic activity changes; some weak indications for a 12 yr periodicity were found, but were rated as “poor” in terms of false-alarm probability by the authors. During the last years, the large-scale magnetic field of τ Boo was reconstructed from spectropolarimetric measurements using Zeeman Doppler Imaging (Catala et al. 2007; Donati et al. 2008; Fares et al. 2009). These reconstructions suggested that the polarity of the large-scale magnetic field switched

* Corresponding author: katja.poppenhaeager@hs.uni-hamburg.de

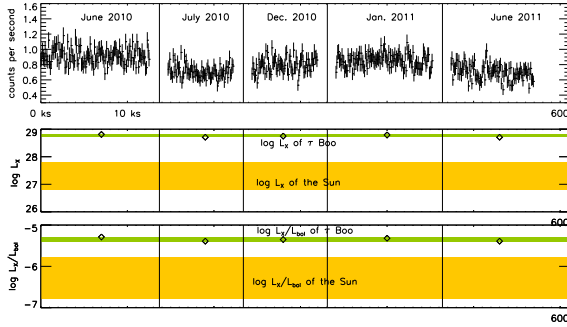


Fig. 1 (online colour at: www.an-journal.org) *Upper panel:* background-subtracted X-ray lightcurves of τ Boo in 2003 and 2010/11 with 100 s time binning, observed with the XMM-Newton PN camera; *middle panel:* range of $\log L_X$ of τ Boo (green) in comparison to the range covered by the Sun during an activity cycle (yellow); *lower panel:* same for range of $\log(L_X/L_{\text{bol}})$.

twice during a period of two years, indicating an activity cycle of only one year duration.

If these reconstructions really characterize the actual magnetic field configuration of the star, it can be expected in analogy to the Sun that τ Boo is in a state of minimum activity during the phases of a stable, poloidal field configuration. During the polarity switches, when toroidal field configurations are dominant, the activity level should be at a maximum. The available Zeeman Doppler Imaging (ZDI) data suggest that the polarity switches occur yearly in winter; our observations therefore cover several winter and summer pointings to look for systematic changes.

2 Observations and data analysis

2.1 X-ray data

We monitored τ Boo's X-ray emission with the XMM-Newton telescope in five observations so far; see Table 1. Additionally, there is an archival XMM-Newton observation of the star from June 2003. The data from this observation has been analyzed in detail by Maggio et al. (2011); however, we have re-analyzed the dataset along the same lines as we have done for our new observations from 2010/11 for better comparability. All observations were performed with XMM-Newton's thick filter, as τ Boo is an optically bright target with $m_V = 4.5$. This is also the reason why the optical monitor of XMM-Newton had to be blocked and could not be used for scientific analysis.

We reduced the data using standard procedures of the SAS10.0 software package. τ Boo has a mean X-ray count rate of $\approx 0.8 \text{ cts s}^{-1}$, practically all photons have energies below 5 keV, except for the observation in 2003 where also few X-ray source photons of higher energies were collected. We produced light curves with 100 s binning to obtain acceptable error bars as well as enough time resolution to

identify possible flares. For the spectra, we used energy bins with at least 15 counts per bin for decent statistics. We extracted EPIC CCD spectra with moderate spectral resolution as well as high-resolution grating spectra from the two RGS instruments. Significant background signal was present for the 2003 observation, so in analyzing this exposure we used good time intervals with low background signal to extract the source spectra. The spectral fitting was performed with Xspec v12.5.

τ Boo has a stellar companion at an angular distance of $2.8''$ (Patience et al. 2002) which is unresolved in the XMM-Newton observations. This companion, GJ 527 B, is a low-mass main-sequence star of spectral type M2. The majority of early M dwarfs ($\approx 80\%$) have luminosities below $\log L_X = 27.5$ (Schmitt et al. 1995). This amounts to a fraction of only 5 % of the detected X-ray flux of both τ Boo and GJ 527 B together, so that we can safely choose to neglect the contribution of the low-mass companion to the X-ray emission in our observations.

2.2 Optical data from FLWO

The Fred Lawrence Whipple Observatory in Arizona hosts the TRES spectrograph at its 1.5-m telescope. TRES is a cross-dispersed echelle spectrograph with a resolution of $\approx 20\,000$ – $40\,000$ (depending on the fiber used) in a bandpass covering 3900 – 9100 \AA . For our observations the medium fiber was used, yielding a spectral resolution of $\approx 30\,000$. The raw spectra were flatfielded and the wavelength calibration was conducted through ThAr reference frames, using the TRES reduction pipeline.

Optical data is available for June and July 2010 as well as for April and July 2011; in the 2010 observations, a total observation duration of ca. 30 minutes was reached, split into several individual pointings. In 2011, the star was observed during three nights each, yielding a total exposure time of ca. 1.5 h.

3 Results

3.1 X-ray lightcurves

The X-ray lightcurves of τ Boo, collected in summer 2003, summer 2010, winter 2010/11, and summer 2011, are shown in Fig. 1. The lightcurves were extracted from the PN detector in the 0.2 – 5 keV energy band. The median count rate in the 2003 observation was higher than in any of the later observations with ca. 1.0 cts s^{-1} . The 2010/11 observations displayed median count rates of 0.90, 0.69, 0.79, 0.85, and 0.70 cts s^{-1} , respectively. All lightcurves display some short-term variability of 10–30 %. The 2003 observation exhibits several small flares, and also the 2010/11 observations show a few flare-like variations on a very low level. However, the flares are too small to allow a detailed loop analysis.

A convenient way to characterize the variability of the light curves with a single number is the Median Absolute

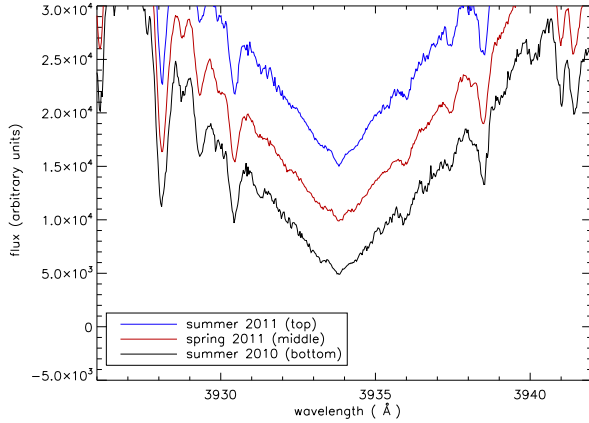


Fig. 2 (online colour at: www.an-journal.org) Ca II K line of τ Boo in summer 2010, spring 2011, and summer 2011; the spectra are vertically shifted for better visibility. The emission in the line core is practically unchanged.

Table 2 X-ray luminosity (0.2–10 keV), activity indicator L_X/L_{bol} and MAD (see text for explanation) during the five observations of τ Boo.

Date	L_X (erg s^{-1})	$\log \frac{L_X}{L_{\text{bol}}}$	MAD	State
2003 Jun	7.6×10^{28}	-5.22	0.090	min.
2010 Jun	6.5×10^{28}	-5.29	0.072	min.
2010 Jul	5.1×10^{28}	-5.39	0.050	min.
2010 Dec	5.6×10^{28}	-5.35	0.072	max.
2011 Jan	6.1×10^{28}	-5.32	0.069	max.
2011 jun	5.1×10^{28}	-5.39	0.059	min.

Deviation (MAD). It is defined as the median of the absolute deviations from the median in each individual lightcurve, explicitly $MAD = \text{med}(|X_i - \text{med}(X_i)|)$, with X_i being the measured count rates per time bin of the light curve. The MAD values for each observation are given in Table 2.

3.2 Activity levels

A good indicator for coronal activity is the ratio of X-ray and bolometric luminosity. Inactive stars typically display values of $\log(L_X/L_{\text{bol}}) < -6$; the Sun's activity index varies between -6.8 and -5.8 during an activity cycle (Judge et al. 2003).

We compute the mean X-ray luminosity of τ Boo in each of the five observations by fitting MOS, PN and RGS spectra in Xspec 12.0 with a VAPEC model with four temperature components and variable abundances for the most prominent elements visible in the X-ray spectra, which are oxygen, neon, iron, magnesium, and silicon. We calculate the X-ray luminosity in the 0.2–10 keV energy band and the activity indicator from the spectral model, the results are given in Table 2. In cool stars, the activity indicator typically spans values of -7 to -3, placing τ Boo at a moderate level of activity which is higher than the solar activity

level at the maximum of the solar cycle. The highest X-ray activity level was detected in summer 2003, where the X-ray luminosity was higher by 50 % compared to the lowest activity level detected in July 2010 and June 2011.

The chromospheric activity level can be determined from the optical spectra we recorded. The core of the Ca II K line, located at wavelengths around 3933 Å, is depicted in Fig. 2. There is a small amount of emission in the line core, typical for a low to moderate level of activity. To quantify this emission, we calculate the equivalent width of the Ca II K line core, contained in a 1 Å part of the spectrum centered around the minimum of the core, with respect to the pseudo-continuum present between 3945 and 3955 Å. The values are very similar for the optical observations with $EW_{\text{summer 2010}} = 0.987$ Å, $EW_{\text{spring 2011}} = 0.989$ Å, and $EW_{\text{summer 2011}} = 0.978$ Å. Further observations to be obtained in 2011/12 will give more insight into the variability of τ Boo's chromospheric activity.

4 Discussion

Our observations have shown that τ Boo is a moderately active star which displays some small-scale variability in X-rays. However, using the data available up to now, we do not find evidence for a short activity cycle of ≈ 1 yr duration. Especially an elevated activity state in winter 2010/11 as extrapolated from spectropolarimetric measurements is not present in the stellar coronal emission.

This is not a problem of identifying stellar activity cycles in X-ray emission. It has been shown for two stars other than the Sun, namely HD 81809 and 61 Cyg (Favata et al. 2008; Hempelmann et al. 2006), that the quasi-quietest coronal emission in general follows the chromospheric activity behavior. For these stars, the activity cycles with approximately 8 and 10 yr are much longer than the one that was proposed for τ Boo.

This leaves two main reasons why the coronal emission does not show the expected long-term variability. On the one hand, the sampling of our data available so far is quite sparse with only four pointings distributed over one year. It might be that we incidentally caught τ Boo in short phases of low activity during winter 2010/11, while the general activity level during that period was significantly higher. For the observations from 2003, a low activity state was extrapolated from the spectropolarimetric data. If truly a 1-year cycle is present, then there are seven cycles between that dataset and the 2010/11 observations. We know from the Sun that different activity cycles can be more or less pronounced, so the higher activity level in 2003 does not necessarily contradict this interpretation.

On the other hand, the magnetic polarity switches reconstructed from spectropolarimetric measurements might not be caused by a short magnetic cycle in the first place. In those observations, the Stokes I and V components were measured, and the magnetic field reconstructions then yield

mainly information on the *net* magnetic field of the stellar hemisphere that is visible during the individual observations. Areas on the stellar surface which have opposite polarity “cancel out” in the Stokes V signal and can therefore usually not be reconstructed by measuring only these two components. If these areas and their magnetic fields differ slightly, the Stokes V signature appears as that of the net field strength of both areas, and thus does not allow a distinction between global net fields and a locally differing field strength of opposite polarity.

In the case of τ Boo, a net radial magnetic field with a strength of up to 10 G has been reconstructed (Fares et al. 2009). In the Sun, the magnetic field strength in sunspots is of the order of several kilogauss, while the global polar field of the Sun is much weaker with only a few Gauss. Even if sunspots usually are present in pairs, it is well possible that a snapshot of one stellar hemisphere of τ Boo contains local magnetic fields in such a way that their integral over the stellar disk yields a net field strength equals 10 G.

5 Conclusion

In our ongoing observational campaign we monitor the coronal and chromospheric activity of τ Boo to test for a short activity cycle as predicted from spectropolarimetric observations. We have collected X-ray and optical data over a period of one and a half years which show that τ Boo is a star of moderate and slightly variable activity. However, our data do not show indications for an activity cycle of one year duration.

Poppenhäger, K., Robrade, J., Schmitt, J. H. M. M., & Hall, J. C. 2009, A&A, 508, 1417
 Saffe, C., Gómez, M., & Chavero, C. 2005, A&A, 443, 609
 Schmitt, J. H. M. M., Fleming, T. A., & Giampapa, M. S. 1995, ApJ, 450, 392

Alonso, R., Auvergne, M., Baglin, A., et al. 2008, A&A, 482, L21
 Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269
 Barnes, S. A. 2001, ApJ, 561, 1095
 Catala, C., Donati, J., Shkolnik, E., Bohlender, D., & Alecian, E. 2007, MNRAS, 374, L42
 Donati, J., Moutou, C., Farès, R., et al. 2008, MNRAS, 385, 1179
 Fares, R., Donati, J., Moutou, C., et al. 2009, MNRAS, 398, 1383
 Favata, F., Micela, G., Orlando, S., et al. 2008, A&A, 490, 1121
 Hempelmann, A., Robrade, J., Schmitt, J. H. M. M., et al. 2006, A&A, 460, 261
 Judge, P. G., Solomon, S. C., & Ayres, T. R. 2003, ApJ, 593, 534
 Maggio, A., Sanz-Forcada, J., & Scelsi, L. 2011, A&A, 527, A144
 Metcalfe, T. S., Basu, S., Henry, T. J., et al. 2010, ArXiv e-prints
 Patience, J., White, R. J., Ghez, A. M., et al. 2002, ApJ, 581, 654